Exploring Earth’s magnetic field – Three make a Swarm

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Exploring Earth's magnetic field – Three make a Swarm[1]

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Introduction

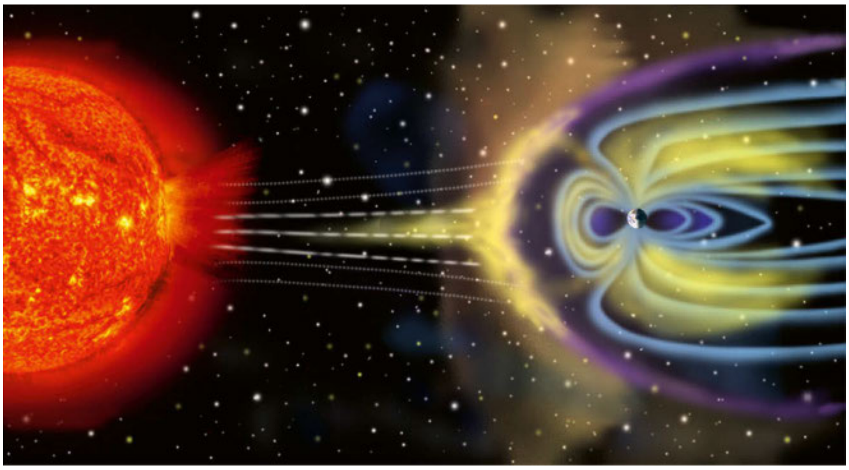
It is amazing how many important aspects of great impact in our everyday life are still largely enigmatic to us. The Earth's magnetic field is a good example – it belongs to the most mysterious aspects of our habitat. Indeed, the electromagnetic field in and around Earth generates complex forces that have innumerable effects on our daily environment and life.

The geomagnetic field provides a huge shield that protects us from harmful solar charged particles and cosmic rays. Without this protection, life in its current form would not exist. Although it might not appear so at first glance, the Earth's magnetic field is permanently changing: the magnetic north pole wanders – currently several tens of kilometres per year – and every few hundred thousand years the polarity of the Earth's magnetic field flips. The field strength is constantly changing too – at present significantly weakening. Over the last 100 years, the dipole part alone has decreased by 7%. However, in certain areas on Earth, for instance in the Southern Atlantic, the weakening of the geomagnetic field is even stronger. Since this is the region of lowest field intensity on Earth, any further weakening is of particular concern.

The geomagnetic field extends from Earth's interior out into space where it interacts with the solar wind, the stream of charged particles emitted by the Sun. Most of the Earth's magnetic field is thought to be generated by an ocean of liquid iron that makes up Earth's outer core, 2900 km under our feet – there, temperatures are about 4500 °C, so that the molten iron resembles the viscosity of water. Acting like the spinning conductor in a bicycle dynamo, this "geodynamo" generates electric currents and thus the continuously changing electromagnetic field[2]. However, our understanding of how exactly the Earth's dynamo works and why it changes is still very limited. For example, computer models that reproduce some of its features have only been developed in the last few decades.

Not only the Earth's core contributes to the geomagnetic field, other sources of magnetism are magnetised rocks in the Earth's crust, with the ionosphere, the magnetosphere and even the oceans also playing a role. The resulting field is a superposition of all these effects. It is thus a major task to observe and measure the complex and constantly changing geomagnetic field as precisely as possible in order to advance many areas of Earth science. In addition to terrestrial observations, highly accurate and frequent measurements of the magnetic field from space can provide new insight into our planet's formation, dynamics and the entire environment stretching from the Earth's core to outer space.

Figure 1: Artist's rendition of Earth's magnetosphere (not to scale, credit: NASA).



[1] The current issue of *Spatium* has been drafted by Dr. Anuschka Pauluhn, based on a seminar by Prof. Nils Olsen on March 27, 2019 in the pro ISSI series. Support from Prof. Martin C.E. Huber and Dr. Andreas Verdun is gratefully acknowledged.

[2] The term electromagnetic here is used to describe the fields generated by varying currents rather than electromagnetic wave (AC) phenomena, thus it refers to currents and permanent magnetic fields.

The first space missions to measure the terrestrial magnetic field were launched in the 1960s, but they measured only its magnitude, not its direction. After the brief lifetime of the Magsat mission (7 months in 1979 and 1980), which carried the first space-borne high-precision vector magnetometer, the Danish Ørsted satellite measured the magnetic vector field for more than 15 years from 1999. The German CHAMP mission continued to do so from 2000 to 2010.

In 2000, ESA launched the Cluster mission to measure the field farther out: four satellites to study the interaction of the solar wind with Earth's own magnetic field that creates the terrestrial magnetosphere (see also *Spatium* 9 by G. Paschmann). The Cluster satellites are relatively far from Earth in elliptical orbits ranging from 19 000 km to 119 000 km. ESA's more recent task force investigating the Earth's magnetic field, the constellation of the Swarm satellites, continues the work started by Ørsted and CHAMP. Launched in 2013, the three Swarm satellites operate much closer to Earth than Cluster, at a maximum distance of around 500 km. The two missions thus collect complementary data on a quantity that is of paramount importance for a variety of studies related to our planet – the geomagnetic field.

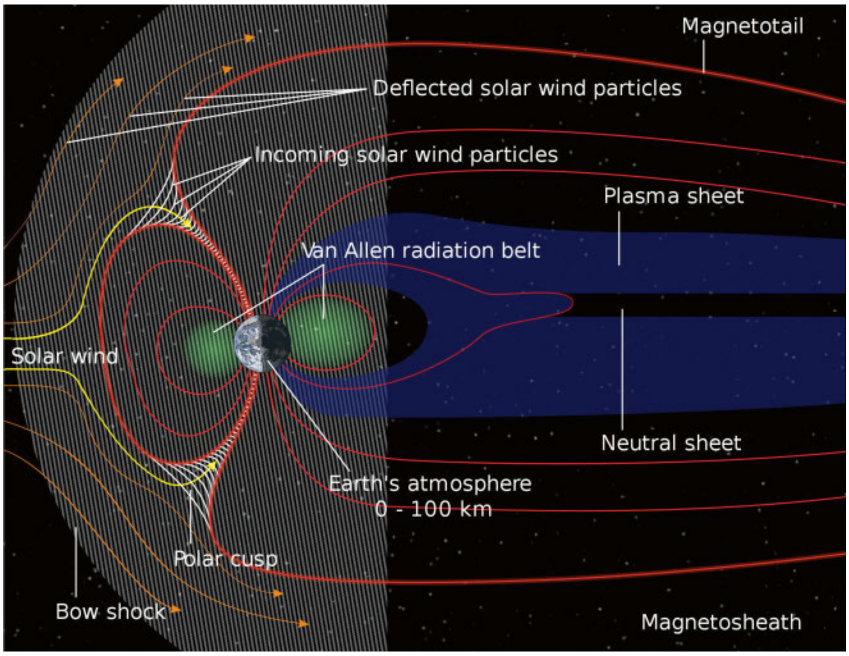


Figure 2: Earth's magnetosphere. All that can be studied from Cluster to Swarm. (Credit: NASA).

Some magnetic reference data for comparison:

The magnetic field of a small bar magnet (like "refrigerator" souvenir magnets) at a short distance of about 1 cm: 0.01 T.

The bending magnet (dipole) field in an electron accelerator (on an axis of the machine, which means on the central orbit of the electrons) to deflect the electrons onto a circular path (e.g., at the Swiss Light Source, SLS, in Villigen, CH): 1.4 T.

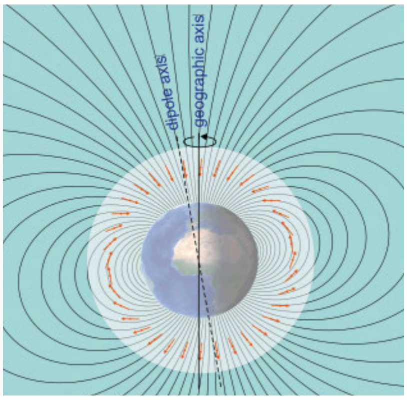
The magnetic field strength in a hospital MRI (magnetic resonance imaging) scanner: 0.5 T to 30 T, i. e., more than 10 000 times stronger than the Earth's magnetic field.

The solar magnetic field[3]: on average 1×10^{-4} T. In sunspots (which are caused by strong localised magnetic fields that prevent the plasma flow within these areas of the photosphere and thus appear darker) the field strength reaches 0.1 T to 0.4 T.

[3] However, note that solar astrophysicists still tend to use the (non-SI) unit gauss (G), with 1 G = 1×10^{-4} T.

Geomagnetism – why is it so interesting?

As first approximation, the terrestrial magnetic field behaves as if there were a powerful bar magnet at the centre of the planet, tilted at about 11° to the axis of rotation (see **Figure 3**). The magnetic field is represented by a three-dimensional vector, and a compass needle is used to measure the direction of its horizontal part; this is the direction of magnetic north in the horizontal at the observer's location. Its angle relative to true geographic north, i. e., the difference between the direction to the geographic north pole and that given by the compass needle, is called the *declination*. The declination is positive for an eastward offset. Knowledge of declination is so crucial for terrestrial navigation by compass that it is often included on maps in the form of a small diagram that shows its value at a certain time along with its current rate of change.



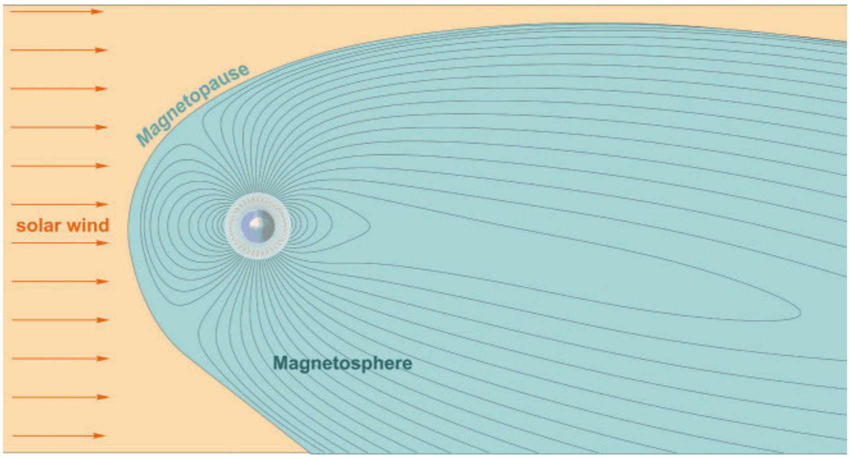


Figure 3:
Left: Undisturbed field lines of the Earth's magnetic field, in the absence of the solar wind. The orange arrows show the direction of the magnetic field near the surface.
Bottom: The constant stream of charged particles emerging from the Sun, the solar wind, compresses the geomagnetic field on the day side and elongates it on the night side. Blue shows the region dominated by the Earth's magnetic field while the region where the influence of the solar wind dominates is shown in yellow.

Anybody steering an airplane or a ship should know how to calculate the true heading of the vessel from the compass reading, correcting for declination.

Facing magnetic north, the angle between the field and the local horizontal plane is called the *inclination,* which can assume values between –90° (up) and 90° (down). In the northern hemisphere the field generally points downwards, straight down at the magnetic north pole, rotates upwards until it is horizontal at the magnetic equator and straight up at the magnetic south pole[4], as shown by the orange arrows in the upper part of **Figure 3**.

The field strength is generally given in nanotesla (nT), the standard SI unit being tesla (T), with 1 nT = 1×10^{-9} T. The geomagnetic field strength at the Earth's surface ranges from 25 000 nT near the equator to 60 000 nT near the poles.

The magnetic field in Bern at the moment (June 2019) has a field strength of 48 000 nT, an inclination of 63° (which means that field lines are more pointing vertically downward than in a horizontal direction even at a non-polar region like Switzerland) and a declination of 3° E.

Approaching the Earth from space, its magnetic field would be noticeable far out (as sketched in **Figure 2**). Let us follow the successive layers

[4] Note that the geomagnetic north would be the south pole of a conventional dipole magnet.

Figure 4: Aurora north of Tromsø, photograph taken on 2nd of January 2013. Credit: Urs Künzler.

from the magnetosphere at some 100 000 km inwards to the core.

Magnetosphere and ionosphere

The extent of the terrestrial magnetosphere in space is determined by the Earth's magnetic field. Interaction with the solar wind compresses the Earth's magnetic field on the day side where the boundary is at a distance of about 60 000 km from Earth's centre. The magnetosphere protects the Earth from charged particles of the solar wind and cosmic rays, which would otherwise strip away the upper atmosphere, including the ozone layer that protects the Earth from ultraviolet radiation. On the night side, the magnetosphere is elongated and deformed into a "tail" that extends to several hundred thousands of kilometres. Closer to Earth, at altitudes roughly between 80 km and 1000 km, is the location of the ionosphere, the part of the Earth's atmosphere that is ionised by solar UV radiation and thus contains free positive ions and electrons. In the sunlit hemisphere, we therefore have more charged particles, leading to higher conductivity and consequently enhanced electric currents relative to the night side. This causes daily geomagnetic variations that are driven by tidal winds in the upper atmosphere[5]. In addition to these diurnal variations, and particularly in polar regions, enhanced solar activity causes irregular disturbances in the ionosphere and magnetosphere. These result in the polar lights, also called the aurora (borealis or australis, depending on

[5] The tidal winds are excited by thermal or gravitational forces, propagate into ionospheric altitudes and generate currents by dynamo action.

their occurrence around the northern or southern poles). They are generated when charged particles originating from the solar wind are channelled along Earth's magnetic field lines into the atmosphere in the so-called auroral ovals. These are bands of roughly 25 to 35 degrees surrounding the magnetic poles with positions varying according to the solar activity[6]. When these charged particles collide with neutral atoms and molecules – mainly oxygen and nitrogen – in the upper atmosphere, some of the energy resulting from these interactions excites the atoms so that they radiate the visible green-blue light that is typical of the aurorae. A photograph of an aurora is shown in **Figure 4.**

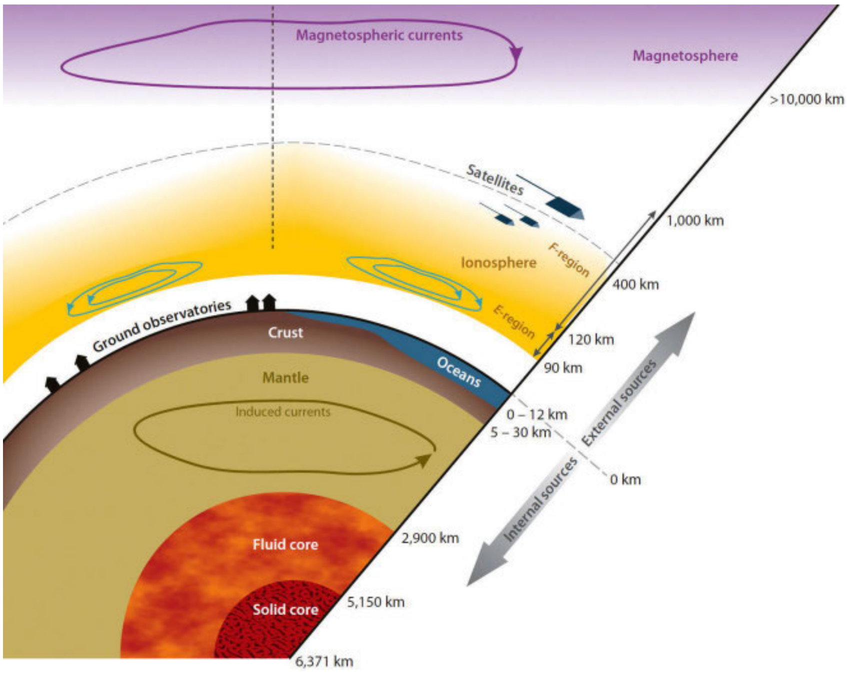


Figure 5: Schematic of the various current systems and sources contributing to the geomagnetic field.

Crust and core

Only a small fraction of the magnetic field, on average about 3%, is generated by electric currents in space surrounding Earth. Another small fraction, also about 3%, of the field is due to magnetised rocks in the upper lithosphere[7], which constitutes the rigid outer part of the Earth, consisting of the crust and upper mantle down to depths between 5 km below oceans and 30 km below continents. Since the salty seawater is electrically conducting, tidal motions in the oceans make an additional, albeit weak, contribution to the magnetic field. In the electrically conducting crust and mantle, minute magnetic signals are generated due to induced currents caused by time-varying electric currents in the ionosphere and magnetosphere. The conductivity structure is related to composition, temperature and water content and can thus be used for geological studies. All these magnetic signals are very difficult to separate. However, Swarm, being a constellation of three satellites and thus measuring the magnetic field simultaneously at different places, has been designed for exactly this kind of source separation.

The overwhelmingly largest part of the geomagnetic field, about 94%, is created at depths greater than 2900 km by the movement of molten iron in the Earth's outer core. The core is a region of mainly iron alloys extending outwards to about 3480 km (the radius of the Earth is 6370 km). It is divided into a solid inner part with a radius of 1220 km and a liquid outer part. The motion of the liquid in the outer core is driven by convection due to the heat flux from the inner core, which has a temperature of about 5700 °C, to the core-mantle boundary, which has about 3500 °C. The heat is generated by

[6] The "aurora chasers", people in search of the spectacular polar lights, are most interested in these areas.
[7] The lithosphere (from the Greek λίθος, lithos, rocky, and σφαῖρα, sphaira, sphere) consists of the rather rigid outermost shell, the crust and mantle. The "softer", highly viscous, mechanically weaker, more easily deforming part of the mantle below the lithosphere is called asthenosphere (from ’ασθενής, asthenes, weak).

potential energy released by heavier materials sinking towards the inner core as well as by the decay of radioactive elements. In fact, this means that there is a huge mass of iron below our feet half-way down to the centre of Earth that is liquid and swirling around, like in a cup of coffee. The flow-pattern of this metal liquid stems from forces due to contact of the liquid with the solid inner core and also with the solid lower surface of the mantle and the rotation of the Earth. **Figure 5** shows a sketch of the various sources that contribute to the magnetic field.

Most planets of the Solar System and the Sun as well as other stars generate magnetic fields via such a dynamo process[8]; exceptions are, however, the planets Mars (which presently has no active dynamo but had one in the past) and Venus.

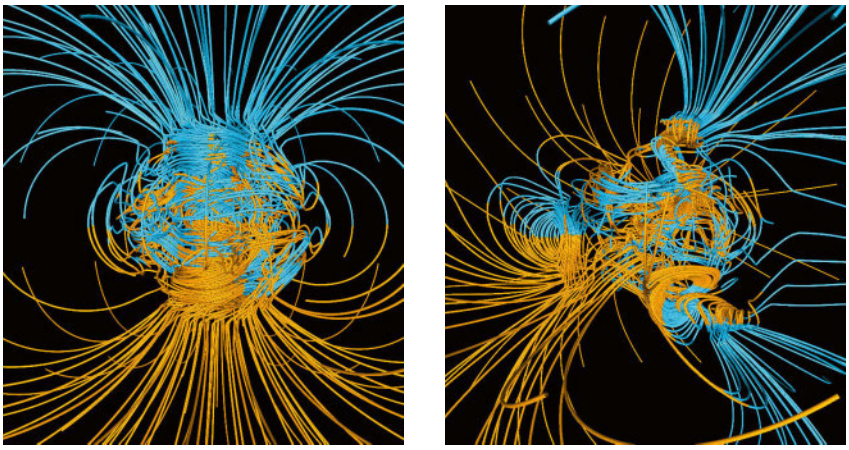


Figure 6: Computer simulation of the Earth's magnetic field in a period of normal polarity between reversals (left) and during a reversal (right). The lines represent magnetic field lines, blue when the field points towards the centre (north) and yellow when away (south). The rotation axis of the Earth is centred and vertical. The dense clusters of lines are within the Earth's core. Credit: University of California, Santa Cruz.

Geophysics from space

One of the very few ways of probing the Earth's liquid core is to measure the magnetic field it creates and to monitor the field changes over time. Due to the very high electric conductivity of the molten iron alloy in the outer core, magnetic field lines are "frozen" in the material and thus move with the fluid. Magnetic field lines can thus be used as tracers of core flow, analogous to drifting buoys used by oceanographers to study ocean flow. In this way, variations in the magnetic field directly reflect the fluid flow in the outermost core. Evidence for changes on a longer time scale, i. e., of previous geomagnetic reversals can be detected in basalts, sediment cores, and magnetic anomalies found on the seafloor. These polarity reversals have occurred occasionally and nearly randomly in time in the history of the Earth, on time scales ranging between less than 100 000 years and 50 million years. During the last 20 million years there was, on average, one reversal in 250 000 years, but the last time this happened was about 780 000 years ago, so Earth might be overdue for a reversal. **Figure 6** shows computer-simulated geomagnetic field lines for a normal polarity configuration and during a reversal.

The continuous changes in the core field that result in motion of the magnetic poles and reversals are important for the study of the Earth's lithosphere, also known as the crustal field, which has both, induced parts (induced by the strength and direction of the present core field), and remnant-magnetised parts. The latter depend on the magnetic properties of the subsurface rock and the history of Earth's core field, which imprinted its direction and strength into the rock at the time when the rock was created. We can therefore also learn a lot about the history of the magnetic field and geological activity by studying magnetism in the Earth's crust.

As new oceanic crust is created through volcanic activity on the seafloor, the magnetisation of iron-rich minerals in the upwelling magma is aligned with the ambi-

[8] The solar dynamo for example has a polarity reversal half period of about 11 years, the solar cycle.

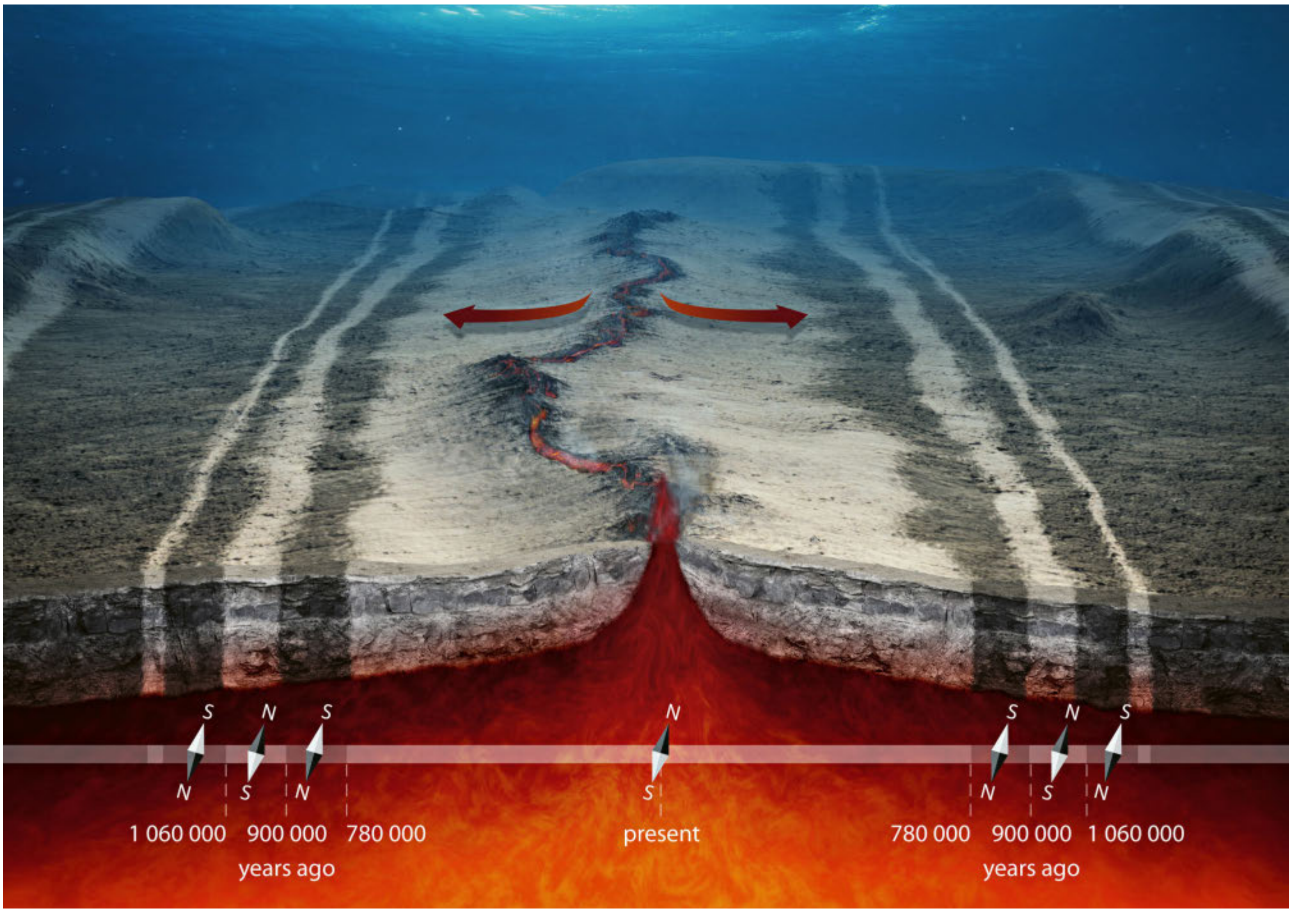


Figure 7: The seafloor as geological tape recorder. Pole reversals are imprinted in the seafloor. As new oceanic crust is created through volcanic activity, the magnetisation of iron-rich minerals in the upwelling magma is oriented to magnetic north at the time. These magnetic stripes are evidence of pole reversals. Credit: ESA/AOES Medialab.

ent magnetic field at the time of the process, and this information is stored when it cools down and solidifies. The magnetic "zebra" stripes (seen in **Figure 7**) are evidence of the pole reversals. Thus, analysing the magnetic imprints on the ocean floor permits the reconstruction of the past core field and concurrently helps to investigate tectonic plate motion. Knowledge about these magnetic stripes is still rather young, only in the 1960s were they assigned to magnetic field reversals. At the same time, new dating techniques, involving radioactive decays of isotopes, were established, and these provided a more accurate determination of volcanic rock age. Together with the imprinted magnetic orientation, the history of field reversals can thus be reconstructed. In particular, the magnetic patterns on the floor of the oceans are correlated in a way that shows how they had been spreading from several centres and had moved away at a rate of several centimetres per year. Thus, finally, geomagnetism provided confirmation of the plate tectonic movements and the so-called continental drifts stated by Alfred Wegener in 1912 and by several scientists before him.

Three's a Swarm

The three identical Swarm satellites (called Alpha, Bravo and Charlie), launched on 22 November 2013, are ESA's first so-called constellation mission for Earth observation[9]. Flying in constellation means that a set of several spacecraft are operated in such a way that their relative distances are measured and controlled. The satellite orbits were carefully selected in order to optimise separation of the different sources of magnetism. The three satellites were placed in two different polar orbits. Two satellites, Swarm Alpha and Charlie, started off flying side by side at an altitude of, initially, 470 km, separated by about 1.4 degrees in longitude (corresponding to 150 km at the equator), thus measuring the east-west magnetic gradient. Over the life of the mission, they will descend naturally to an altitude of about 300 km and below. The third satellite, Swarm Bravo, has been placed at an altitude of 530 km. The satellites' orbit planes drift in local time (due to precession since they are not exactly crossing the

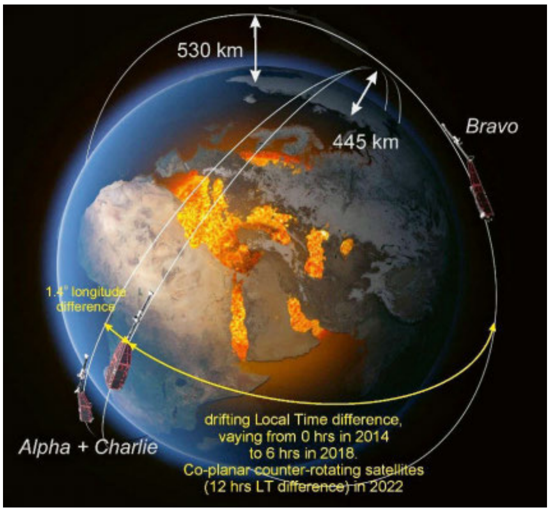


Figure 8: The Swarm constellation. The three identical satellites have a rather unusual shape: trapezoidal with a long boom that was deployed once they were in orbit. In stored configuration, the satellites had to be compact enough to all fit into one launcher fairing! Credit: ESA/ATG Medialab.

geographic poles), resulting in the upper satellite having crossed the path of the lower pair at an angle of 90° – or 6 hours in local time difference – in 2018. These drifting orbits mean that all the magnetic signals originating from Earth's interior and its environment can be measured and separated in an optimal way.

The instruments:

The **vector field magnetometer** is the mission's core instrument. It makes high-precision measurements of the magnitude and direction of the magnetic field.

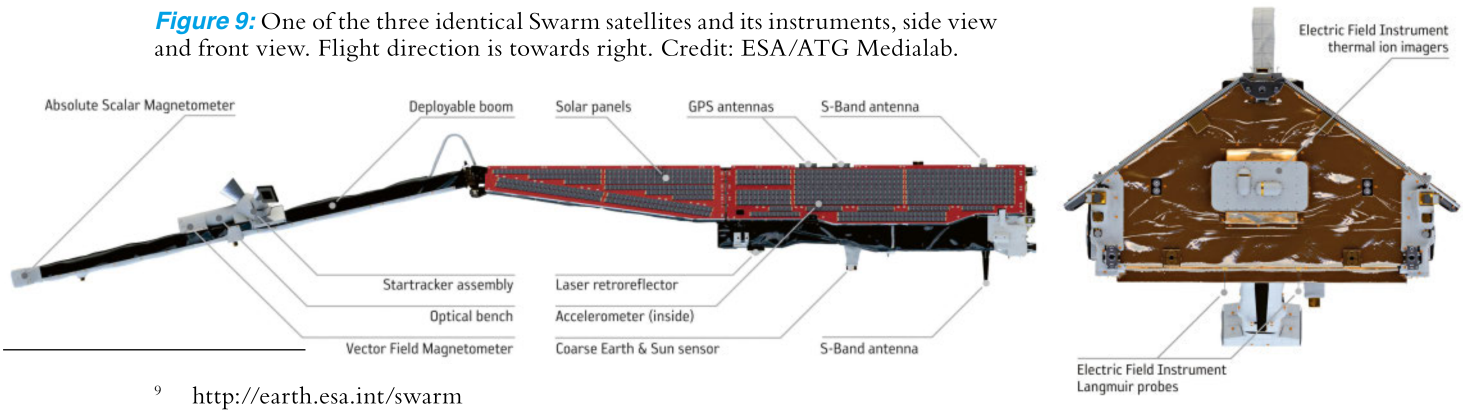
The **absolute scalar magnetometer** measures the strength of the magnetic field to a greater accuracy than any other magnetometer. Both magnetometers have been placed on the boom in order not to be affected by magnetic disturbances due to electric currents flowing in the spacecraft or the other instruments.

The **electric field instrument,** positioned at the front of each satellite, measures plasma density, temperature and drift in high resolution to characterise the electric field around Earth.

The **accelerometer** measures the satellite's non-gravitational acceleration in its respective orbit and, in turn, provides information about air drag and solar wind.

The **GPS receivers,** the **star tracker** and the **laser retroreflector** measure the position and attitude.

Figure 9: One of the three identical Swarm satellites and its instruments, side view and front view. Flight direction is towards right. Credit: ESA/ATG Medialab.



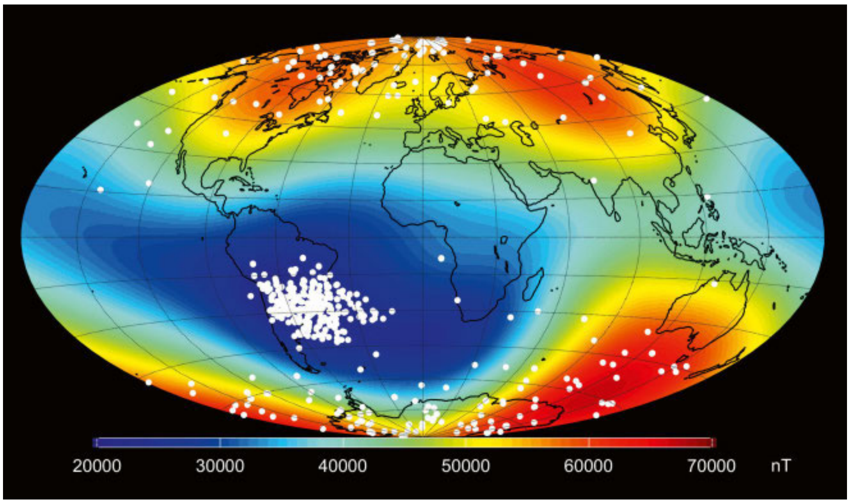
9 http://earth.esa.int/swarm

A Swarm of detectives

Magnetic field on the move

In June 2014, after just six months collecting data, Swarm had already delivered a wealth of information on the terrestrial magnetic field. A snapshot of early Swarm data is shown in **Figure 10.** The asymmetry of the field is clearly seen, and the tilt of the Earth's rotation axis with respect to the main dipole axis and the offset of the dipole from Earth's centre give rise to the weak field in the South Atlantic. In some areas, such as the southern Indian Ocean, the measurements showed that the magnetic field had strengthened since January of the same year although globally the field has weakened, with the most dramatic declines in the western hemisphere. The measurements also verified the movement of the magnetic north pole towards Siberia. These changes might be hinting at a polarity reversal of the geomagnetic field. As will be described below, further Swarm observations along with advanced modelling have already given an idea of how these developments are based on the changing magnetic signals stemming from the Earth's core and the flow of iron around it.

Figure 10: "Snapshot" of the main magnetic field at Earth's surface as of June 2014 based on Swarm data. The measurements are dominated by the magnetic contribution from Earth's core while the contributions from other sources (the crust, oceans, ionosphere and magnetosphere) make up the rest. Red represents areas where the magnetic field is stronger, while blue shows areas where it is weaker. The South Atlantic Anomaly (SAA) is the near-Earth region where the Earth's magnetic field is weakest. The white spots on this map indicate where the instruments on the Swarm satellites were disturbed by charged particles. Credit: DTU Space.



Magnetic structures in high resolution

Combining Swarm data with the data from earlier satellite missions like CHAMP and using new modelling techniques, it was possible to generate the highest-resolution map ever of the magnetic signals of the upper lithosphere. Global resolution of about 300 km is provided by the unique satellite data coverage (**Figure 11**). In regions like Australia, additionally densely covered with near-surface data, the resolution is even higher: locally up to 30 km, providing a detailed map of the crustal magnetisation, as shown in **Figure 12**.

A new model of the geomagnetic field

The World Magnetic Model (WMM) – the reference when it comes to navigation – is usually updated every five years. Actually, this schedule has been pushed forward one year due to the recent acceleration of the shift of the magnetic north pole from 15 km per year 50 years ago to presently about 55 km per year. The Swarm mission contributed significantly to tracking the unexpected movement. Based on the current WMM[10], the 2019 location of the north magnetic pole is 86.54° N and 170.88° E, and the location of the south magnetic pole is 64.13° S and 136.02° E, see **Figure 13.** Surely, this information is of major interest for many of us. Numerous peo-

[10] WMM2015v2, the "out-of-cycle" model released beginning of 2019.

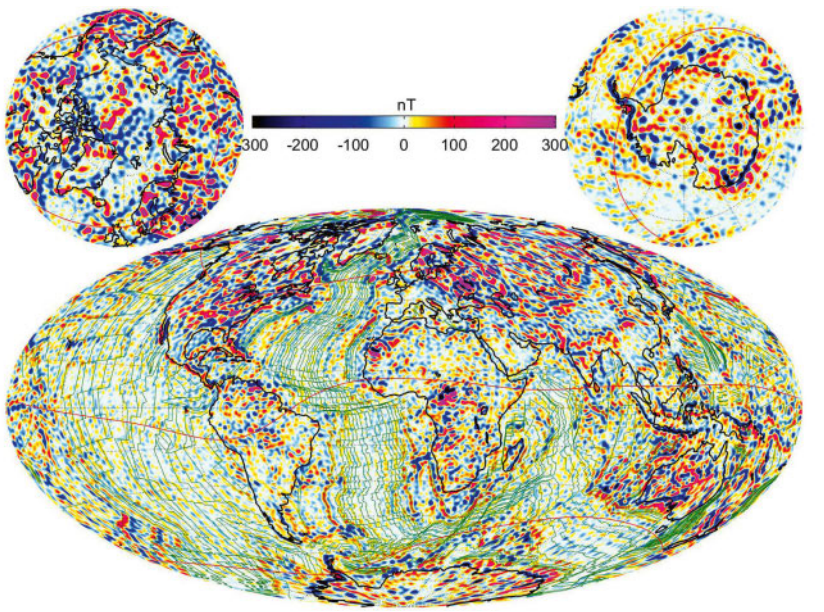


Figure 11: Global model of the lithospheric field, derived from CHAMP and Swarm data (Olsen et al 2017).

ple use these data continuously, even if they are unaware of it, because in general a smartphone contains a magnetometer that measures the Earth's magnetic field. In order to make sense of this information, the devices' operating systems use the magnetic model to correct the measurements to true geographic north.

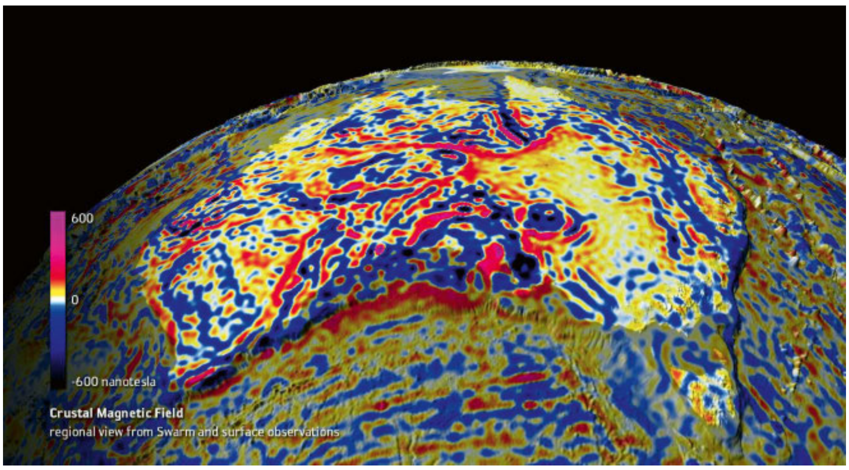
Improving the theory

Physical descriptions of the geomagnetic field should be as comprehensive as possible and include all known magnetic sources and their interactions. The goal is to represent the field in high spatial and temporal resolution in order to describe the small-scale structure of the core and crustal fields as well as their spatial and temporal variations. For example, 20 years of data from the CHAMP, Ørsted, and Swarm satellites as well as from 160 ground observatories have been used to improve the latest models such as the LCS-1 lithospheric field model (Olsen et al 2017) or the CHAOS-6 core field model (Finlay et al 2016). The latter describes Earth's magnetic field with 32 600 model parameters that are estimated from 7.6 million observations.

The iron jet stream

Most people are familiar with the jet streams in the atmosphere, the fast flowing and rather narrow, meandering currents of air. Swarm observations revealed such a pattern of magnetic flux patches like a daisy chain in the northern hemisphere, mostly under Alaska and Siberia, in the Earth's molten outer core (cf., **Figure 14**). The measurements show an intense field change at high latitude, centred on the north geographic pole. The observed patterns can be explained by a jet stream of liquid iron of a width of 420 km at the core surface, i. e., at a depth of around 2 900 km, moving at nearly 50 kilometres per year (Livermore et al 2017). This is three times faster

Figure 12: The most detailed map ever of the tiny magnetic signals generated by Earth's lithosphere. The map has been composed from four years of measurements from the Swarm satellites, historical data from the German CHAMP satellite and observations from ships and aircraft. (Released 2018, credit: ESA/Planetary Visions).



than typical outer core speeds and hundreds of thousands times faster than the speed at which the Earth's tectonic plates move. The stream marks the boundary between two different core regions and is probably driven by buoyancy or by changes in the magnetic field within the core. Based on a combination of data from the Ørsted, CHAMP, and Swarm satellites as well as from ground-based observatories, it was found that the jet has increased its velocity by a factor of three over the period 2000 to 2016 to the present speed. This means that this jet is now stronger than typical flows near the core. It is suggested that the present accelerating phase may be part of a longer-term fluctuation of the jet, shuffling magnetic features over historical periods, and that it may contribute to the rotation direction of the inner core. This is also consistent with recent computer models.

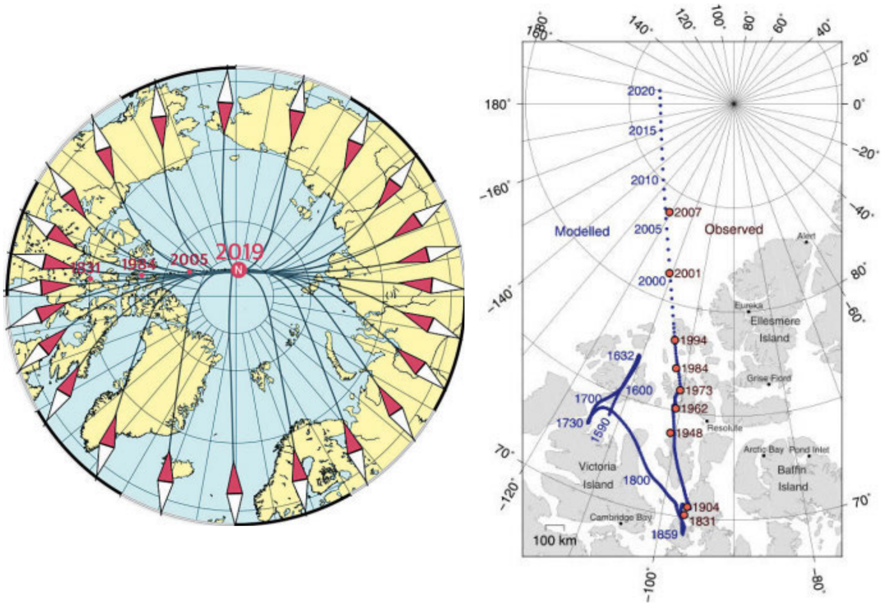
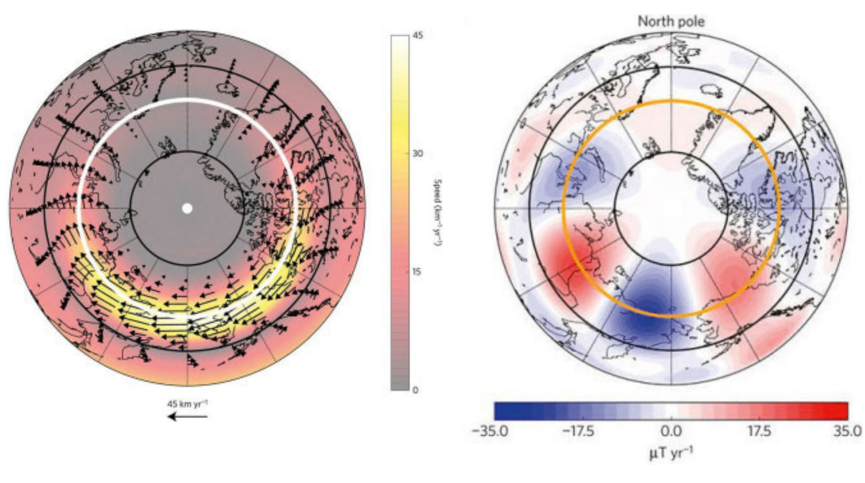


Figure 13: Driven largely by the motion of fluid in the Earth's core, which generates the magnetic field, the magnetic north pole has always drifted. Around 50 years ago, the pole was ambling along at around 15 km a year, but now it is speeding up at around 55 km a year, leaving the Canadian Arctic and heading towards Siberia. (Credit: DTU Space.)

The signal from the oceans

The Earth's oceans are a conductive fluid owing to dissolved ions. As the water moves around in current flows and tides, it generates an electric current and therefore a faint magnetic field that is observable from space. Although its weak signatures are extremely hard to detect, the lunar M2 tide could clearly be identified as an outstanding signal. Moreover, by analysing more than five years of magnetic observations by Swarm it has also been possible to extract two even weaker tidal components: the O1 diurnal tide and the N2 semidiurnal tide (Grayver and Olsen 2019). Swarm data thus could be used to measure the magnetic signals of tides from the ocean surface to the seabed. This renders a truly global picture of how the ocean flows at all depths and presents an alternative way of measuring how tides and currents move in three dimensions. Tracking how the heat in the oceans is distributed and stored, particularly at depth, is increasingly important for understanding our changing climate. Going even further, this tidal magnetic signal also induces a weak magnetic re-

Figure 14: The accelerating high-latitude jet at the core surface (left) is able to explain the observed magnetic field change at Earth's surface (right) (from Livermore et al 2017).



sponse due to current closure deep under the seabed, and thus permits us to learn more about the electrical properties of the Earth's lithosphere and upper mantle.

Strange blackouts

During the first two years of Swarm's operation, their GPS connection was broken 166 times. This kind of blackout has been observed before, happening sometimes to low-orbiting satellites flying over the equator between Africa and South America. Measurements with Swarm, monitoring simultaneously high-resolution GPS data and ionospheric patterns, could establish a direct link to ionospheric "thunderstorm"-like phenomena, around 300 km to 600 km above Earth (Xiong et al 2016). These thunderstorms occur when the number of electrons in the ionosphere undergoes large and rapid changes, which tends to happen close to the Earth's magnetic equator and typically just for a couple of hours between sunset and midnight. Such a thunderstorm event scatters the free electrons in the ionosphere, creating small bubbles with little or no ionised material. These bubbles disturb the GPS signals so that the Swarm GPS receivers can lose track. Obviously, these results are interesting for upper-atmosphere dynamics as well as for the development of more robust GPS receivers.

Who is Steve?

The "ordinary" aurorae are well known to be green, blue or red and possibly last for minutes to hours. They form when the magnetic field guides energy and charged particles in the solar wind around Earth and towards the north and south poles. When these particles interact with atoms and molecules in the upper atmosphere, the familiar waves of luminous green light of the aurora borealis and aurora australis appear in the night sky. However, in 2016 a group of citizen scientist auroral photographers reported repeatedly observing a dynamic, very thin, east-west-aligned purple aurora-like structure significantly equatorward of the usual auroral oval near the poles. Lacking, as yet, any explanation or proper naming convention, the phenomenon had been dubbed "Steve"[11]. Subsequently, matching Steve sightings to Swarm passes, one of the satellites directly flew through the arc, and measurements of the ambient plasma could be performed. The plasma temperature 300 km above Earth's surface jumped by 3000 °C and the data revealed a 25 km-wide ribbon of gas flowing westwards at about 6 km/s compared to a speed of about 10 m/s either side of the ribbon. The strong flow, being a plasma density depletion, and a temperature enhancement hinted towards a kind of sub-auroral ion drift. Such transient events with supersonic westward flows confined within a narrow region of space in the evening (near midnight) sector just equatorward of the traditional auroral oval had been observed before, however never in this optical wavelength range. Although the occurrence of this phenomenon is quite frequent, many questions still remain, for example the emission in the dominant purple colour needs further examination. Finally, the name ***S**trong **T**hermal **E**mission **V**elocity **E**nhancement* was given to this peculiar phenomenon to acknowledge the amateur scientists as well as the professionals. While Steve is created through the same general process as a normal aurora, it travels along different magnetic field lines and therefore can appear at much lower latitudes where the alignment of the global electric and magnetic fields makes ions and electrons flow rapidly in the east-west direction, heating them in the process (MacDonald et al 2018).

Figure 15: Steve and the Milky Way at Childs Lake, Manitoba, Canada. The picture is a composite of 11 images stitched together. Credit: Krista Trinder.

[11] "Let's call it Steve" is a reference to a 2006 animated movie "Over the Hedge" in which the animal characters named a shrubbery Steve because they did not know what it was.

Outlook

The Swarm experiment is currently funded through to 2021. Given the excellent health of the satellites and their payload, an extension beyond that is feasible and strongly endorsed by scientists and ESA's scientific advisory board. Any further long-term study of the magnetic field and its sources, in particular covering a full solar cycle, is highly desirable for various applications. This, of course, strongly applies to geophysics, like the study of the dynamics of the outer core of the Earth or its lithospheric magnetic field. It is also interesting to interpret the magnetic field data in combination with gravity and seismic measurements. Moreover, the Swarm data contribute significantly to studies of the terrestrial ionosphere and magnetosphere. This is highly useful when it comes to better understanding of the processes responsible for space weather, the conditions in the terrestrial atmosphere defined by the solar activity and interaction with the interplanetary magnetic field, which can have a serious impact on various human affairs. Monitoring geomagnetic storms due to solar flaring and coronal mass ejections can protect electric power grids on Earth – as well as satellites and humans travelling in planes and spacecraft.

The constellation setup of the satellites is a key asset that makes the Swarm mission so extremely useful and unique. Additionally, in an attempt to improve the spatio-temporal characterisation of all phenomena observed by Swarm further, the lower pair geometry will be modified in order to support studies that directly target the complicated electrodynamics of the ionosphere. Concretely, this will entail bringing the orbital planes of the lower pair even closer together than they are today, to reach co-planarity in 2021 (when the third, higher, satellite will also be counter-rotating in the same orbital plane), and at the same time varying the along-track separation. The preparations for these activities are ongoing and actual implementation of orbital correction manoeuvres will take place in autumn 2019.

These orbit modifications are part of the plan to extend the mission far beyond its original lifetime and science objectives, with the perspective to measure Earth's magnetic field with Swarm – at least with the higher satellite Swarm Bravo – for an additional decade. This will prolong the continuous time series of space measurements, which began with the launch of the Ørsted satellite in 1999, to 30 years.

Credit: C. Barton.

Further reading/Literature:

Spatium No 9, Paschmann, G., The Fourfold Way through the Magnetosphere: The Cluster Mission, June 2002.

Finlay, C.C., Olsen, N., Kotsiaros, S., Gillet, N. and Tøffner-Clausen, Recent geomagnetic secular variation from Swarm and ground observatories as estimated in the CHAOS-6 geomagnetic field model. Earth, Planets, Space, 68, 112, doi: 10.1186/s40623-016-0486-1, 2016.

Grayver, A. and Olsen, N., The Magnetic Signatures of the M2, N2, and O1 Oceanic Tides Observed in Swarm and CHAMP Satellite Magnetic Data, Geophys. Res. Lett., doi: 10.1029/2019GL082400, 2019.

Livermore, P. W., Hollerbach, R., Finlay, C.C., An accelerating high-latitude jet in Earth's core, Nature Geoscience 10, 62, 2017.

MacDonald, E. A., Donovan, E., Nishimura, Y. (plus 13 authors), New science in plain sight: Citizen scientists lead to the discovery of optical structure in the upper atmosphere, Science Advances, 4 (3), eaaq0030, doi:10.1126/sciadv.aaq0030, 2018.

Olsen, N., Ravat, D., Finlay, C.C., and Kother, L.K., LCS-1: A high-resolution global model of the lithospheric magnetic field derived from CHAMP and Swarm satellite observations, Geophys. J.Int. 211 (3), 1461{1477, doi:10.1093/gji/ggx381}, 2017.

Sabaka, T.J., Tøffner-Clausen, L., Olsen, N., Finlay, C.C., A comprehensive model of Earth's magnetic field determined from 4 years of Swarm satellite observations, Earth, Planets and Space, 70, 130, https://doi.org/10.1186/s40623-018-0896-3, 2018.

Xiong, C., Stolle, C., Lühr, H., The Swarm satellite loss of GPS signal and its relation to ionospheric plasma irregularities, Space Weather, https://doi.org/10.1002/2016SW001439, 14, 2016.

The Author

Nils Olsen is a physicist with more than 150 peer-reviewed publications. He studied physics, geophysics and meteorology at the TU Darmstadt and Göttingen University in Germany. After receiving his PhD in physics on geomagnetic daily variations from Göttingen University, he worked at Copenhagen University and the Danish Space Research Institute on the exploitation of magnetic observations taken by the Ørsted and CHAMP satellites. Building on this experience, he collected an international team together to perform an "End-To-End mission simulation" for the Swarm satellite constellation with the goal of investigating the benefits of different orbital constellations and thereby arguing for a mission design that maximises scientific return. He is a member of the ESA Mission Advisory Group for Swarm and of the Advisory Board "German Geomagnetic Observatories", and serves as the Danish National Delegate of the International Association of Geomagnetism and Aeronomy.

Nils is now full Professor of Geophysics at the Technical University of Denmark and Principal Investigator of the Swarm Data, Innovation, and Science Cluster. His research interests include the various contributions to Earth's magnetic field from the core to the magnetosphere, and how they can be separated and used for exploring the Earth's interior and its environment.